Probability of induced seismicity associated with large-scale underground hydrogen storage in salt formations of northwestern Europe

N. Van Den Ameele[1,2], H. Hajibeygi[1], H. Van Gent[2], A. Muntendam-Bos[1,2]

[1] Delft University of Technology; [2] Dutch State Supervision of Mines

Summary

As underground hydrogen storage (UHS) is expected to play a key role in future renewable energy systems, understanding the potential geomechanical risks, such as induced seismicity, is essential. Therefore, this study aims to assess the probability of induced seismicity associated with the prospect of large-scale UHS plans. We commence by developing simulation models with increasing complexity, starting from the basic characteristics of the salt formation, salt cavern, and operational conditions, and progressing to the inclusion of structural features within the salt formation as well as in the overburden and sideburden. A 2D finite element simulator is used to incorporate deformation and simulate creep behaviour, which is subsequently coupled with a rate-and-state Coulomb threshold model to compute the seismicity rate from stress changes. The developed framework accounts for the geological and mechanical characteristics of the heterogeneities that influence local stress fields, allowing us to identify conditions that may increase seismic risk or enhance stability.

Probability of induced seismicity associated with large-scale underground hydrogen storage in salt formations of northwestern Europe

Introduction

In recent years, there has been a strong push to transition from fossil fuels to sustainable energy resources to achieve a net-zero emission energy system by 2050. Future energy systems will likely depend heavily on intermittent renewables such as wind and solar, requiring solutions to balance supply and demand (Zivar et al. 2021). Large-scale underground hydrogen storage (UHS) in salt caverns offers a promising approach to provide seasonal balancing, manage bulk energy, and enhance strategic energy security (Juez-Larré et al. 2023; Kountouris et al. 2024). However, UHS in salt caverns comes with potential geomechanical risks, one of which is induced seismicity (Foulger et al. 2018; Muntendam-Bos et al. 2022).

Induced seismicity associated with salt caverns is often linked to cavern instability or collapse (Ford and Dreger, 2020; Kinscher et al. 2015). However, micro-seismic events have also been recorded during regular leaching and storage operations. In such cases, seismic monitoring serves as a near real-time risk assessment tool to manage and maintain cavern integrity (del Potro et al. 2016; Fortier et al. 2019, 2015; Renoux et al. 2013; Shemeta et al. 2013). In areas under evaluation for hydrogen storage in salt caverns, ongoing monitoring has revealed frequent low-magnitude seismic events ($-2.0 \leq Mw \leq 1.0$), although the underlying mechanisms are still not well understood (Bosq et al. 2020; Muntendam-Bos et al. 2022). As interest in UHS grows, increased activity in salt caverns is expected, highlighting the need to better understand the causes of observed seismicity and assess the potential for induced events related to expanding UHS operations.

This study aims to assess the probability of induced seismicity associated with large-scale UHS prospects. We seek to analyse and quantify the mechanisms behind seismicity induced by salt cavern leaching and cyclic operation by: (1) developing representative, yet simplified simulation models based on salt formation characteristics, cavern geometry, and operational conditions; (2) incorporating additional complexities such as intra-salt layers, overburden, irregular cavern shapes, and pressure variations; (3) quantifying stress and deformation evolution; and (4) applying a rate-and-state Coulomb threshold model to assess seismic activity. In the absence of rigorous studies specific to rock salt, we adopt the rate-and-state Coulomb threshold model, originally developed for porous rocks, as an initial step toward a comprehensive, full-physics analysis for rock salt.

Method and/or Theory

We use observations from existing leaching and storage caverns in the Netherlands as a starting point to understand the geological and operational conditions relevant for future hydrogen storage. In northeastern Netherlands and northern Germany, the rock salt formations of the Permian Zechstein Group are particularly suitable for this purpose (Caglayan et al. 2020). Most caverns in this region have been developed in the Z2 and Z3 halite layers within salt domes and pillows. The Z2's primary thickness exceeded 500 m and is subdivided by thin anhydrite/polyhalite beds. The Z3 comprises a claystone-carbonate-anhydrite-halite sequence, with anhydrite layers reaching up to 45 m (Strozyk et al. 2017; Van Gent et al. 2011). These insoluble layers can complicate cavern development by affecting drilling operations, cavern shape, deformation behaviour, and local stress fields. Although these features pose engineering challenges, the high solubility and mechanical properties of the Z2 and Z3 halite continue to make them favourable targets for the creation of salt caverns (Wong et al. 2007).

While these formations offer favourable conditions, internal heterogeneities like anhydrite and carbonate layers add complexity and may contribute to induced seismicity. Smit et al. (2024) proposed several physical mechanisms that may cause seismic events near salt domes with active storage. These include fault (re)activation in the overburden and underburden, upward force from the dome's rising movement, velocity differences due to internal heterogeneities such as anhydrite floaters, and operational triggers like cavern collapse, roof rockfalls, pressure and temperature changes, and irregular cavern shapes.

To investigate these mechanisms, we use a 2D finite element simulator (Ramesh Kumar et al. 2021; Ramesh Kumar and Hajibeygi, 2022) that accounts for non-linear primary and secondary deformation to simulate salt creep. It includes both dislocation and pressure-solution creep, the latter being a key deformation mechanism at low deviatoric stress levels (typically below 5 MPa), relevant to UHS (Rowan et al. 2019). The simulations are done to obtain the deformation (strain) field over time (Honório et al. 2024; Honório and Hajibeygi, 2024). From these deformation data sets, stress changes are computed, which are then used to compute normal and shear stress variations. Coulomb stress change is then calculated and used as input into a rate-and-state Coulomb threshold model (Heimisson et al. 2021). This model computes seismicity rates based on time-dependent stress evolution, (fault) activation thresholds, and fault orientations. Note that to keep the simulation model simple, faults are not explicitly modelled in the simulation framework. As such, the stress-strain fields are obtained assuming no fault exists in the geo-system, and then after for every fault, the stress is projected into the normal and tangential directions to the fault plate.

Systematic simulation models have been developed to explore the seismic response surrounding salt caverns under various geological and operational scenarios. The reference models consist of cylindrical caverns at varying depths in homogeneous halite. These are then expanded to incorporate geological heterogeneities typical of Zechstein formations, such as overburden, sideburden, and brittle or ductile intra-salt layers, as well as operational factors like irregular cavern geometries and pressure cycles. Cavern pressure has been simulated across key operational stages: initial solution mining, subsequent brine discharge, two years of cyclic hydrogen storage/production, and finally a slow return to 100% lithostatic pressure (i.e., representative of the abandonment phase). These simulations aim to realistically represent the pressure variations experienced during typical cavern operation lifetime (Pajonpai et al. 2022).

Sample section

Figure 1 presents conceptual reference models. In Figure 1a, a simulation setup is shown with a cylindrical cavern embedded in homogeneous halite. The operational cycle, shown in Figure 1b, is applied to the cavern wall, with pressure expressed as a percentage of the lithostatic pressure. The cycle consists of one year of solution mining, one year of brine discharge at constant pressure, two years of annual hydrogen injection and production cycles (at 60–80% of lithostatic pressure), followed by one year during which the cavern pressure is slowly returned to 100% of lithostatic pressure. This configuration is not intended to represent a specific real-world cavern but serves as a generic test case to explore seismic responses under controlled conditions.

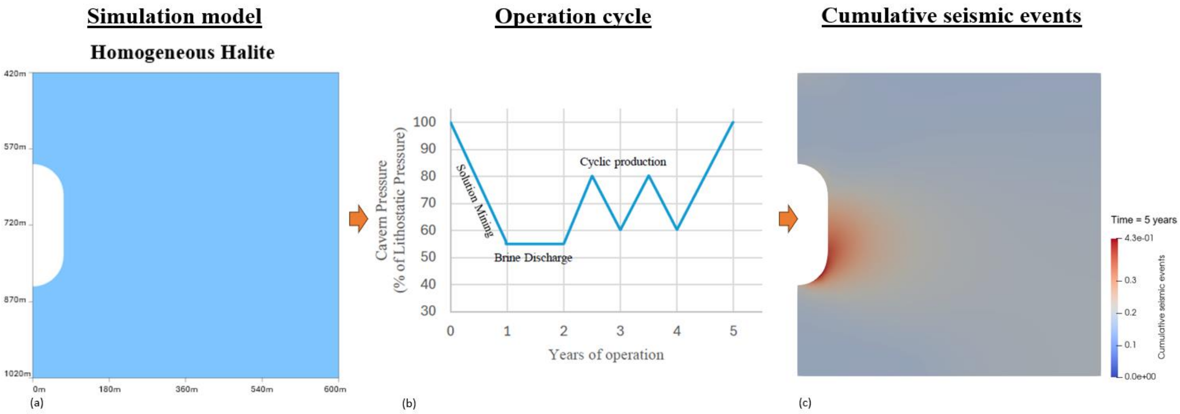

Figure 1 *Reference model setup and resulting seismicity. (a) Simulation model with a cylindrical cavern embedded in homogeneous halite at 600m depth, (b) applied pressure cycle, consisting of*

solution mining phase, brine discharge, cyclic injection/production and return to 100 % of lithostatic pressure, and (c) cumulative number of seismic events.

Conclusions

As hydrogen storage in salt caverns becomes more important to future energy systems, understanding the risk of induced seismicity is essential. To achieve this, we use a numerical modelling approach that combines a finite element simulator with a rate-and-state Coulomb threshold model, to explore how geological features and operational conditions influence stress evolution and seismic activity. The framework helps identify conditions that may elevate seismic risk or, conversely, offer stability. The full results and analysis will be detailed in forthcoming work.

While the developed framework is presented for a simple cavern, it is worth highlighting that the simulator and the seismicity assessment model are generic enough to incorporate any level of heterogeneity and complex cavern shapes. Specifically, they allow for the incorporation of non-halite porous layers, which can act as shear zones. Depending on the geological and mechanical characteristics of the heterogeneities, the strategy developed in this work can be used to identify zones with a high probability of seismicity and to design appropriate monitoring schemes for careful observation during operation.

References

Bosq, H., Wijermars, E., Lubkowski, Z., 2020. Using continuous microseismic surveillance for the management of cavern fields. Presented at the Solution Mining Research Institute (SMRI) Fall 2020 Virtual Technical Conference.

Caglayan, D.G., Weber, N., Heinrichs, H., Linßen, J., Robinius, M., Kukla, P.A., Stolten, D., 2020. Technical potential of salt caverns for hydrogen storage in Europe. International Journal of Hydrogen Energy 45, 6793–6805. https://doi.org/10.1016/j.ijhydene.2019.12.161

del Potro, R., Di Giandomenico, S., Roulet, V., Favret, F., Maisons, C., 2016. Statistical analyses of microseismicity in salt cavern storages. Presented at the Solution Mining Research Institute (SMRI) Fall 2016 Technical Conference.

Ford, S.R., Dreger, D.S., 2020. Pre-Sinkhole Seismicity at the Napoleonville Salt Dome: Implications for Local Seismic Monitoring of Underground Caverns. Seismological Research Letters 91, 1672–1678. https://doi.org/10.1785/0220190224

Fortier, E., Barbieri, E., Matrullo, E., Coppenhall, M., Del Potro, R., 2019. Monitoring salt caverns through passive seismic surveillance at the Hill Top gas storage facility -- Characterization of events source. Presented at the Solution Mining Research Institute (SMRI) Fall 2019 Conference.

Fortier, E., Gombert, B., Baud, P., 2015. Monitoring of a Leaching Process on Salt Caverns Using Passive Micro- Seismic Surveillance Geosel Underground Storage. Presented at the Solution Mining Research Institute (SMRI) Fall 2015 Technical Conference.

Foulger, G.R., Wilson, M.P., Gluyas, J.G., Julian, B.R., Davies, R.J., 2018. Global review of human-induced earthquakes. Earth-Science Reviews 178, 438–514. https://doi.org/10.1016/j.earscirev.2017.07.008

Heimisson, E.R., Smith, J.D., Avouac, J.-P., Bourne, S.J., 2021. Coulomb threshold rate-and-state model for fault reactivation: application to induced seismicity at Groningen. Geophysical Journal International 228, 2061–2072. https://doi.org/10.1093/gji/ggab467

Honório, H.T., Hajibeygi, H., 2024. Three-dimensional multi-physics simulation and sensitivity analysis of cyclic energy storage in salt caverns. International Journal of Hydrogen Energy 94, 1389–1405. https://doi.org/10.1016/j.ijhydene.2024.11.081

Honório, H.T., Houben, M., Bisdom, K., Linden, A.V.D., Borst, K.D., Sluys, L.J., Hajibeygi, H., 2024. A multi-step calibration strategy for reliable parameter determination of salt rock mechanics constitutive models. International Journal of Rock Mechanics and Mining Sciences 183, 105922. https://doi.org/10.1016/j.ijrmms.2024.105922

Juez-Larré, J., Gonçalves Machado, C., Groenenberg, R.M., Belfroid, S.S.P.C., Yousefi, S.H., 2023. A detailed comparative performance study of underground storage of natural gas and hydrogen in the Netherlands. International Journal of Hydrogen Energy 48, 28843–28868. https://doi.org/10.1016/j.ijhydene.2023.03.347

Kinscher, J., Bernard, P., Contrucci, I., Mangeney, A., Piguet, J.P., Bigarre, P., 2015. Location of microseismic swarms induced by salt solution mining. Geophysical Journal International 200, 337–362. https://doi.org/10.1093/gji/ggu396

Kountouris, I., Bramstoft, R., Madsen, T., Gea-Bermúdez, J., Münster, M., Keles, D., 2024. A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. Nat Commun 15, 5517. https://doi.org/10.1038/s41467-024-49867-w

Muntendam-Bos, A.G., Hoedeman, G., Polychronopoulou, K., Draganov, D., Weemstra, C., Van Der Zee, W., Bakker, R.R., Roest, H., 2022. An overview of induced seismicity in the Netherlands. Netherlands Journal of Geosciences 101, e1. https://doi.org/10.1017/njg.2021.14

Pajonpai, N., Bissen, R., Pumjan, S., Henk, A., 2022. Shape design and safety evaluation of salt caverns for CO2 storage in northeast Thailand. International Journal of Greenhouse Gas Control 120, 103773. https://doi.org/10.1016/j.ijggc.2022.103773

Ramesh Kumar, K., Hajibeygi, H., 2022. Influence of pressure solution and evaporate heterogeneity on the geo-mechanical behavior of salt caverns. The Mechanical Behavior of Salt X 407–420. https://doi.org/10.1201/9781003295808-38

Ramesh Kumar, K., Makhmutov, A., Spiers, C.J., Hajibeygi, H., 2021. Geomechanical simulation of energy storage in salt formations. Sci Rep 11, 19640. https://doi.org/10.1038/s41598-021-99161-8

Renoux, P., Fortier, E., Maisons, C., 2013. Microseismicity Induced Within Hydrocarbon Storage in Salt Caverns, Manosque, France – Hazard Review and Event Re-location in a 3D Velocity Model. Presented at the Solution Mining Research Institute (SMRI) Fall 2013 Technical Conference.

Rowan, M.G., Urai, J.L., Fiduk, J.C., Kukla, P.A., 2019. Deformation of intrasalt competent layers in different modes of salt tectonics. Solid Earth 10, 987–1013. https://doi.org/10.5194/se-10-987-2019

Shemeta, J., Leidig, M., Baturan, D., 2013. Passive Seismic Observations at Grand Bayou, Louisiana, USA associated with the Failure of Oxy Geismar #3 Solution Cavern. Solution Mining Research Institute (SMRI) Fall 2013 Conference.

Smit, R., van den Ameele, N., van Gent, H., Ruigrok, E., Spetzler, J., Muntendam-Bos, A., 2024. Re-assesment of micro-seismicity in a salt dome in the North of the Netherlands. Solution Mining Research Institute (SMRI) Spring 2024 Technical Conference.

Strozyk, F., Reuning, L., Scheck-Wenderoth, M., Tanner, D.C., 2017. The Tectonic History of the Zechstein Basin in the Netherlands and Germany, in: Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins. Elsevier, pp. 221–241. https://doi.org/10.1016/B978-0-12-809417-4.00011-2

Van Gent, H., Urai, J.L., De Keijzer, M., 2011. The internal geometry of salt structures – A first look using 3D seismic data from the Zechstein of the Netherlands. Journal of Structural Geology 33, 292–311. https://doi.org/10.1016/j.jsg.2010.07.005

Wong, T., Batjes, D.A.J., de Jager, J., 2007. Geology of the Netherlands. Edita- KNAW, Amsterdam, p. 354.

Zivar, D., Kumar, S., Foroozesh, J., 2021. Underground hydrogen storage: A comprehensive review. International Journal of Hydrogen Energy 46, 23436–23462. https://doi.org/10.1016/j.ijhydene.2020.08.138